

NEW TORQUE REVERSAL AND SPIN-UP OF 4U 1626–67 OBSERVED BY FERMI/GBM AND SWIFT/BAT

A. Camero–Arranz^{1,2,3}, M.H. Finger^{1,4}, N.R. Ikhsanov^{5,6}, C.A. Wilson–Hodge^{1,5} and
E.Beklen^{7,8}

ABSTRACT

After about 18 years of steadily spinning down, the accretion–powered pulsar 4U 1626–67, experienced a new torque reversal at the beginning of 2008. For the present study we have used all available *Fermi*/GBM data since its launch in 2008 June 11 and over 5 yr of hard X-ray *Swift*/BAT observations (starting from 2004 October up to the present time). From 2004 up to the end of 2007 the spin–down rate averaged at a mean rate of $\sim \dot{\nu} = -4.8 \times 10^{-13} \text{ Hz s}^{-1}$ until the torque reversal reported here. This second detected torque reversal was centered near MJD 54500 (2008 Feb 4) and it lasted approximately 150 days. During the reversal the source also underwent an increase in flux by a fraction of ~ 2.5 . Since then it has been following a steady spin–up at a mean rate of $\sim \dot{\nu} = 4 \times 10^{-13} \text{ Hz s}^{-1}$. We present a detailed long-term timing analysis of this source and a long term spectral hardness ratio study in order to see whether there are spectral changes around this new observed torque reversal.

Subject headings: accretion, accretion disks — binaries: close — pulsars: individual (4U 1626–67) — stars: neutron — X-rays: stars

1. INTRODUCTION

The accreting–powered pulsar 4U 1626–67 was discovered by *Uhuru* (Giacconi et al. 1972). This low mass X–ray binary (LMXB) consists of a 7.66 s X–ray pulsar accreting from an extremely low mass companion (0.04 M_{\odot} for $i = 18^{\circ}$) (Levine et al. 1988). Although orbital motion has never been detected in the X–ray data, pulsed optical emission reprocessed on the surface of the

secondary revealed (Middleditch et al. 1981) the 42 min orbital period, confirmed by Chakrabarty (1998). Most likely the binary system contains a hydrogen–depleted secondary to reach such a short orbital period (Paczynski and Sienkiewicz 1981). The faint optical counterpart (KZ TrA, $V \sim 17.5$) has a strong UV excess and high optical pulse fraction (McClintock et al. 1977, 1980). A persistent 48 mHz quasi-periodic oscillation (QPO) has been detected in the X–ray emission (Shinoda et al. 1990; Kommers et al. 1998). In 2008 Kaur et al. (2008) claimed that the QPO frequency evolution during the previous 22 years changed from a positive to a negative trend, somewhat coincident with the June 1990 torque reversal in this source. Orlandini et al. (1998) inferred a neutron star magnetic field in the range $(2.4\text{--}6.3) \times 10^{12} \text{ G}$, based on the idea that the quasiperiodic oscillation frequency is due to the beating between the pulse frequency and the Keplerian motion at the magnetospheric radius. To compute this magnetic field range a source distance of 5–13 kpc was assumed. This distance range was obtained from measure-

¹National Space Science and Technology Center, 320 Sparkman Drive, Huntsville, AL 35805

²Fundación Española de Ciencia y Tecnología, C/Rosario Pino, 14–16, 28020– Madrid, Spain

³MICINN (Ministerio de Ciencia e Innovación), C/Albacete, 5, 28027, Madrid, España

⁴Universities Space Research Association, 6767 Old Madison Pike, Suite 450, Huntsville, AL 35806

⁵NASA/Marshall Space Flight Center

⁶Pulkovo Observatory, 196140, St. Petersburg, Russia

⁷Physics Department, Middle East Technical University, 06531 Ankara, Turkey

⁸Physics Department, Süleyman Demirel University, 32260 Isparta, Turkey

ments of the optical and X-ray fluxes, assuming that LMXB accretion disks have a very effective X-ray albedo (Chakrabarty 1998, and references therein). Using a ~ 37 keV absorption cyclotron feature found in the 0.1–200 keV *BeppoSAX* spectrum, Orlandini et al. (1998) obtained a value for the magnetic field of $3.2(1+z) \times 10^{12}$ G, where z is the gravitational redshift. The X-ray broad-band continuum was fitted with a low-energy absorption, a blackbody, a power law and a high energy cutoff.

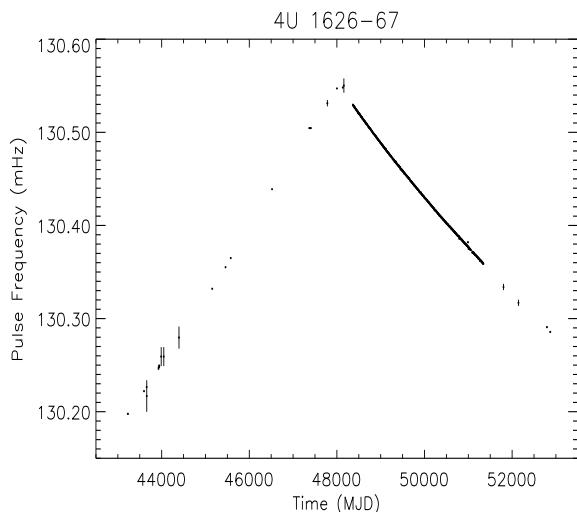


Fig. 1.— Pulse frequency history of 4U 1626–67, showing all available historical data from 1997 to 2003. The 1990 June (\sim MJD 48000) torque reversal is clearly seen.

For more than a decade after the discovery of pulsations (Rappaport et al. 1977) the source underwent steady spin-up at a mean rate of $\sim \dot{\nu} = 8.5 \times 10^{-13} \text{ Hz s}^{-1}$ (Chakrabarty et al. 1997) (see Fig 1). Monitoring of the source by the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory (*CGRO*) starting in April 1991, found the pulsar spinning down, implying a changed sign in the accretion torque (Wilson et al. 1993; Bildsten et al. 1994). During the 7 years after the first torque reversal, the pulsar spun-down at a rate of $\sim \dot{\nu} = -7.2 \times 10^{-13} \text{ Hz s}^{-1}$ (Chakrabarty et al. 1997).

Torque reversals have also been observed in the accreting pulsar systems Her X-1, Cen X-3, GX 1+4, OAO 1657-415, Vela X-1 (Bildsten et al.

1997) and 4U 1907+09 (Inam et al. 2009). The systems most similar to 4U 1626-67 are Her X-1 and Cen X-3, where a persistent accretion disk is known to be present. Her X-1 like 4U 1626-67 has a Roche-lobe filling low mass companion, where matter from the companion flows from the L1 point into an accretion disk (Reynolds et al. 1997). Cen X-3 has a high mass companion which almost overflows its Roche-lobe with a focused wind from companion flowing into the accretion disk (Day and Stevens 1993). Studies of accretion torque in Her X-1 are made difficult by the obstruction caused by the warped accretion disk which is viewed from near edge-on, resulting in attenuation or complete eclipsing of the pulsar (Peterson et al. 1991), making flux measurements unreliable probes of the mass accretion rate. In Cen X-3 the dense wind results in a large column density, with source occasionally being completely obscured. In GX 1+4 (Hinkle et al. 2006), OAO 1657-415 (Chakrabarty et al. 2002), 4U 1907+09 (Fritz et al. 2006) and Vela X-1 (Dupree et al. 1980) the optical companion underfills its Roche lobe and accretion proceeds from a wind, with perhaps the transient formation of an accretion disk if the accreting angular momentum is large enough. Vela X-1 is the prototype for a super-giant wind fed system, where accretion proceeds by direct capture from the wind. In this case the transfer of angular momentum is very inefficient. Detailed timing analysis shows that the frequency history of Vela X-1 is consistent with a random walk, or equivalently the power-spectrum of the torque is white noise (Deeter et al. 1989). However, rare short high-flux states have been observed where transient disk accretion may occur (Krivonos et al. 2003). It is likely that transient accretion disks occur in GX 1+4, OAO 1657-415, 4U 1907+09 and play an essential part in their frequency histories. Understanding the torque behavior of these systems will require characterization of the companion's wind, and detecting the presence or absence of an accretion disk in addition to understanding the flow of angular momentum between that disk and the neutron star. 4U 1626-67 in contrast provides a cleaner laboratory for investigating the flow of angular momentum.

We present a long term timing analysis using all the available *Fermi*/GBM data since its launch in 2008 June 11 and over 5 yr of hard X-ray

Swift/BAT data from 2004 up to 2009. Spectral analysis was also carried out for 4U 1626–67, in order to see changes during this second detected torque reversal that could help us to better understand the physical mechanisms involved in this process.

2. *Fermi*/GBM

2.1. OBSERVATIONS

Since 2008 June 11 4U 1626–67 has been continuously monitored by the *Gamma-ray Burst Monitor* (GBM)(Meegan 2009, submitted), on board the *Fermi* observatory. Timing analysis was carried out with GBM CTIME data, with 8 channel spectra every 0.256 seconds. The total exposure time was ~ 13.75 Ms.

The GBM is an all-sky instrument sensitive to X-rays and gamma rays with energies between ~ 8 keV and ~ 40 MeV. GBM includes 12 Sodium Iodide (NaI) scintillation detectors and 2 Bismuth Germanate (BGO) scintillation detectors. The NaI detectors cover the lower part of the energy range, from 8 keV to about 1 MeV. The BGO detectors cover the energy range of ~ 150 keV to ~ 40 MeV. Only data from the NaI detectors were used in the analysis presented in this paper.

2.2. TIMING ANALYSIS AND RESULTS

The analysis of the *Fermi*/GBM data is complicated by *Fermi*'s continuously changing orientation. All intervals of CTIME data from the 12 NaI detectors are selected for analysis where the high voltage is on, excluding those containing high voltage transients, phosphorescence events, rapid spacecraft slews, South Atlantic Anomaly induced transients, electron precipitation events and gamma-ray bursts. Source pulses are then separated from the background by fitting the rates in all detectors with a background model, and subtracting the best fit model. This model includes bright sources and their changing detector responses, including Earth occultation steps, and quadratic spline functions which account for the remaining long-term background trends. The spline models have statistical constraints on the changes in second derivative between spline segments to control the model stiffness. These fits are made jointly across detectors (with common bright source fluxes) but separately for each

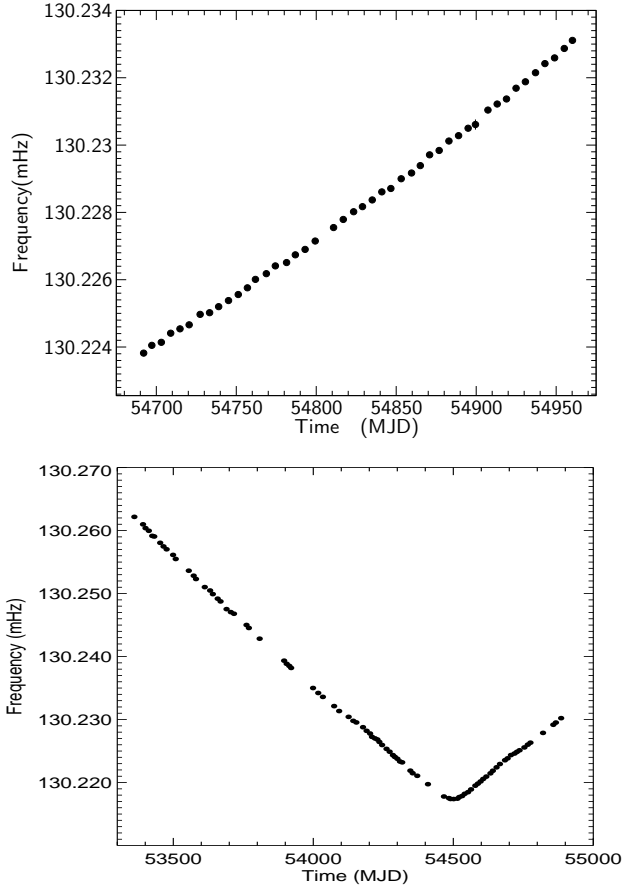


Fig. 2.— Top panel. *Fermi*/GBM pulse frequency measurements of 4U 1626–67 since 2008 August. A change in the sign of the torque was found after 18 years of the source spinning down. Bottom panel. *Swift*/BAT pulse frequency history covering this second reversal (from 2004 Oct to the present time). Error bars are smaller than the plotted symbols.

channel of the CTIME data. Then we combine the residuals over detectors with time dependent weights which are proportional to the predicted (phase averaged) count rates from the pulsar. Short intervals (~ 300 s) of these combined residuals are then fit with a constant plus a Fourier expansion to determine a pulse profile. The profiles are divided into six day intervals and the pulse frequency and mean profile determined in each interval with a search of pulse frequency for the maximum of the Y_n ($n=2$) statistic (Finger et al.

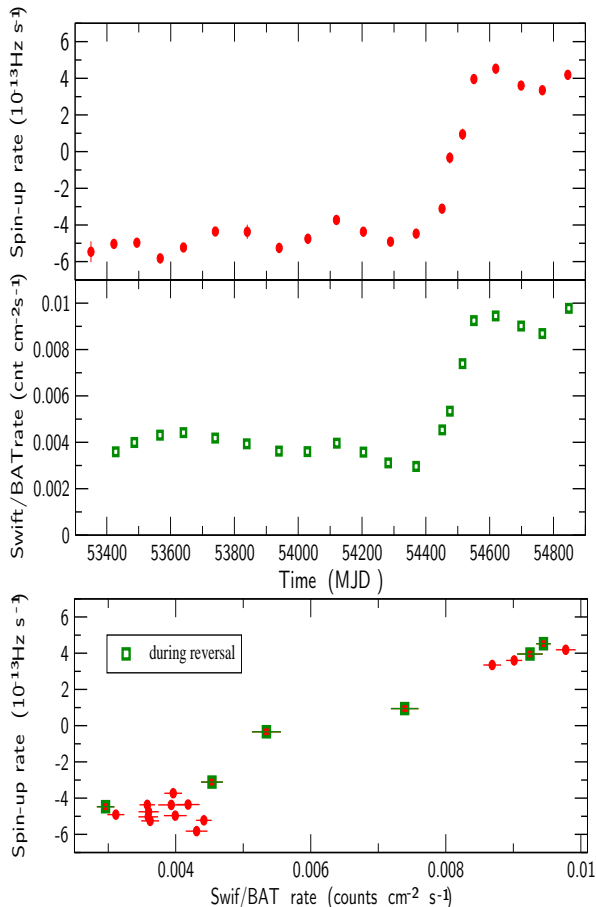


Fig. 3.— Top panel. *Swift*/BAT spin-up rate history of 4U 1626–67. Middle panel. Average 15–50 keV BAT count rate vs. time. Error bars are smaller than the plotted symbols. Bottom panel. BAT count rate vs. spin-up rate for all the period (circles). A correlation pattern is observed specially during the torque reversal (only square symbols).

1999). Y_n was formulated for finding a pulse frequency from a series of pulse profiles, each represented by a finite Fourier expansion, and accounts for possible frequency dependent non-Poisson noise.

Our monitoring of 4U 1626–67 with *Fermi*/GBM starting in 2008 August, found the pulsar again spinning-up rather than spinning-down. Fig 2 shows the pulse frequency history using data from this monitoring. 4U 1626–67 seems to be increas-

ing in $\dot{\nu}$. Follow-up *Fermi*/GBM observations confirm that the pulsar is currently spinning-up at a mean rate of $\sim \dot{\nu} = 4 \times 10^{-13} \text{ Hz s}^{-1}$.

3. *Swift*/BAT

3.1. OBSERVATIONS

The Swift Gamma-ray mission (Gehrels et al. 2004) was launched on 2004 November 20. The hard X-ray (15–150 keV) Burst Alert Telescope (BAT) on board *Swift* monitors the entire sky searching mainly for GRBs. While searching for bursts, BAT also accumulates a hard X-ray survey of the entire sky covering 2 sr at any particular time. Therefore it produces continuous streams of rate data. The rate data include *quadrant rates* (1.6 sec sampling; four energy bands; four separate spatial quadrants), not background subtracted. For the present study we have analyzed more than 4 years of BAT *quadrant rates* observations when 4U 1626–67 was visible (total exposure time ~ 13 Ms). For the hardness ratio analysis we used count rates from the *Swift*/BAT transient monitor results provided by the *Swift*/BAT team¹.

3.2. TIMING ANALYSIS AND RESULTS

A similar procedure was followed for the *Swift*/BAT *quadrant rates* timing analysis. Initial good time interval (GTI) files are obtained using the *maketime* ftool (heasoft-6.6.1)². Then a filtered version of the *quadrant rates* is obtained, rejecting those times when the source is below the horizon, to then finally be barycentered using the ftool *barycorr*. Data are then inspected and cleaned as in the previous section. With the ftool *batmasktiming* the pixel exposure fraction for each quadrant is computed for the center of each (refined) GTI interval. Pulse profiles for each good GTI interval are computed. First the rates for each quadrant are fit to a quadratic+Fourier expansion. Then the Fourier coefficients are combined using the quadrant exposures to produce mean profiles (with units of counts $\text{s}^{-1} \text{ cm}^{-2}$). In a final stage, the Y_n ($n=2$) statistic is again used in intervals of 35 days and a frequency search for

¹<http://heasarc.gsfc.nasa.gov/docs/swift/results/transients>

²<http://heasarc.gsfc.nasa.gov/docs/software.html>

Table 1: *RXTE*/PCA and HEXTE CONTINUUM SPECTRAL FITS^{mod}

Observation (MJD)	α^*	E_{cut}^\dagger	E_{Fold}^\dagger	Gaussian [†]	Gauss. σ^\dagger	Gauss. norm ^{**}	T_{BBod}^\dagger T_{Bremss}^\dagger	norm $BBod^1$ $Brem^2$	Flux ^{***}	χ_r^2 (DOF)
93431-01-01-00 (54530)	0.75(2) 0.74(2)	$18.2^{+0.1}_{-0.3}$ $18.2^{+0.3}_{-0.2}$	8.5(4) $8.5^{+0.3}_{-0.4}$	$6.05^{+0.5}_{-0.17}$ $6.42^{+0.17}_{-0.4}$	$1.6^{+0.3}_{-0.2}$ $1.4^{+0.1}_{-0.2}$	$2.4^{+4}_{-0.8}$ $1.5^{+1.2}_{-0.6}$	$0.615^{+0.006}_{-0.018}$ $1.74^{+0.12}_{-0.14}$	0.0013 0.108	1.01(8) 1.01(1)	1.15(114) 1.15(114)
93431-01-02-00 (54538)	$0.71^{+0.06}_{-0.04}$ $0.71^{+0.04}_{-0.05}$	$17.90^{+0.19}_{-0.3}$ $17.96^{+0.14}_{-0.2}$	$8.4^{+0.5}_{-0.6}$ 8.4(6)	$6.2^{+0.6}_{-0.4}$ 6.9(2)	$1.5^{+0.4}_{-0.2}$ $0.5^{+0.4}_{-0.3}$	$2.23^{+1.9}_{-0.08}$ $0.396^{+0.14}_{-0.015}$	$0.654^{+0.04}_{-0.009}$ $2.47^{+0.3}_{-0.08}$	0.0013 0.068	1.006(12) 1.004(9)	1.29(114) 1.28(114)

^{mod}WABS (GAUSSIAN+ (BLACKBODY or BREMSSTRAHLUNG) +POW) HIGHECUT ($N_H = 1.3 \times 10^{21} \text{ cm}^{-2}$ fixed; Uncertainties:

3 σ level.)

* Photon Index

† keV

** $\times 10^{-3}$

¹ (Lumin/ $10^{39} \text{ erg s}^{-1}$)(d/10kpc)⁻²

² $3.05 \times 10^{-15} (4\pi d^2)^{-1} \times \text{Emission measure}$

*** $\times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ (2–100 keV)

pulsations is carried out. The spin rates were computed by fitting a linear function to the frequencies, which were divided into 21 time intervals.

Swift/BAT observations allowed us to cover the evolution of this second torque reversal. We found that the pulsar spun-down at a mean rate of $\sim \dot{\nu} = -4.8 \times 10^{-13} \text{ Hz s}^{-1}$ until the source reversed torque. Fig 2 shows that the transition took place at around MJD 54500 (2008 Feb 04) and lasted approximately 150 days. In the bottom panel of Fig 3 we can see that there is a strong correlation between the *Swift*/BAT count rate and the spin-up rate especially during the reversal. It is not known if this occurred in the 1990 torque reversal because of the scarce number of observations. In order to see any other possible change, we created pulse profiles in the 15–50 keV band (two harmonics were selected). We have not observed any significant change in pulse shape, not even during the reversal. They all are single-peaked and sometimes not entirely symmetric as was recently reported by Krauss et al. (2007).

4. *RXTE*

4.1. OBSERVATIONS

The Rossi X-ray Timing Explorer (*RXTE*) (Bradt et al. 1993) carries 3 instruments on board. The Proportional Counter Array (PCA) (Jahoda et al. 1996) is sensitive from 2–60 keV. The High Energy X-ray Timing Experiment

(HEXTE) (Gruber et al. 1996) extends the X-ray sensitivity up to 200 keV. Monitoring the long-term behavior of some of the brightest X-ray sources, the All Sky Monitor (ASM) (Levine et al. 1996) scans most of the sky every 1.5 hours at 2–10 keV. Two *RXTE*/PCA observations from 2008 March 5 and 13 were used (ID 93431-01-01-00 and 93431-01-02-00; 7.174 ksec). For spectral analysis we selected PCA Standard-2 data which contains 129-channel range spectra taken every 16 seconds and HEXTE Standard Modes (Archive) data which contains Spectral Bin (64-bin spectra produced every 16s). For the long-term hardness ratio analysis we used the ASM daily flux averages in the 1.5–12 keV energy range from the HEASARC archive³.

4.2. SPECTRAL ANALYSIS AND RESULTS

RXTE/PCA (2.5–20 keV) and HEXTE (18–100 keV) spectra were fitted in XSPEC 11.3.2 with two models used by Pravdo et al. (1979). Using these models allows us to compare our spectral study with previous works by (Pravdo et al. 1979; Orlandini et al. 1998; Krauss et al. 2007; Jain et al. 2009) and update the long-term X-ray flux history of 4U 1626–67 relative to the flux measured by *HEAO 1* (Chakrabarty et al. (1997); Krauss et al. (2007)). The first model includes

³<http://heasarc.gsfc.nasa.gov/docs/archive.html>

a low-energy absorption, a blackbody component, a power law and a high-energy cutoff at ~ 20 keV (WABS (GAUSS+BBODY+POWLAW) HIGHECUT). A broad line near 6.5 keV significantly improves the present fit and indicates the presence of an iron line, also suggested by Pravdo et al. (1979) in their (0.7–100 keV) spectral analysis of this source. The column density of cool material in the line of sight was fixed in our study since it could not be constrained. A value of $1.3 \times 10^{21} \text{ cm}^{-2}$ was selected from Krauss et al. (2007). The spectral parameters obtained are shown in Table 1. Reprocessing of photons either at the base of the accretion column or the inner edge of the accretion disk might explain the

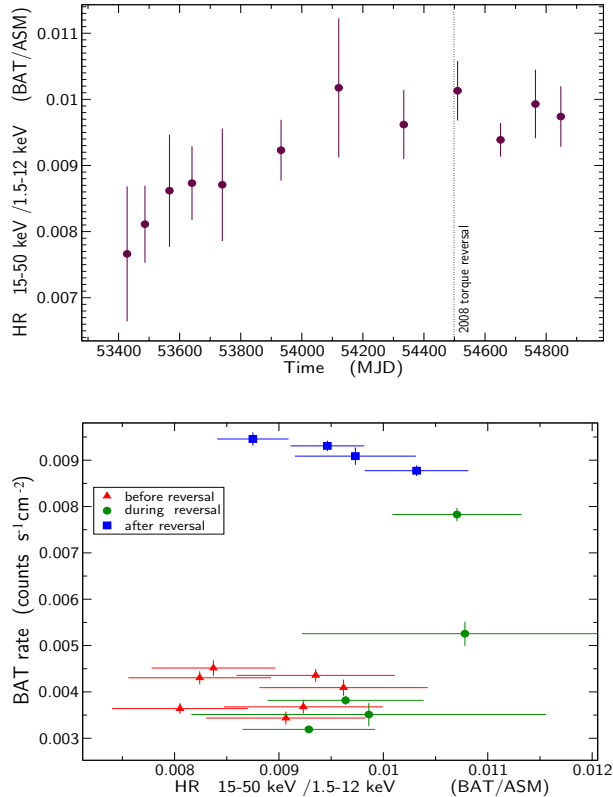


Fig. 4.— Top panel. Long term hardness ratio analysis of 4U 1626–67. *Swift*/BAT count rates (15–50 keV) were selected as the hard band and *RXTE*/ASM count rate (1.5–12 keV) as the soft band. Bottom panel. Hardness–intensity diagram. During the reversal a transition from hard to soft is seen.

origin on the blackbody component. From the blackbody flux and temperature we obtain an emission area of $9 \times 10^{12} \text{ cm}^2$ (assuming a source distance of 10 kpc), which is inconsistent with either of those possibilities. We fit in addition the same model with a bremsstrahlung instead of a blackbody component, obtaining a compatible fit. Table 1 summarizes the spectral parameters obtained. Fluxes for the first model in the 2–10 keV, 2–20 keV and 2–50 keV bands are $3.24(2) \times 10^{-10}$, $7.003(11) \times 10^{-10}$ and $9.98(2) \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$, for the first *RXTE* observation (similar values for the second one).

5. HARDNESS RATIO ANALYSIS

Fig 4 (top panel) shows the hardness ratio (HR) analysis carried out for this source. The HR was defined as the ratio 15–50 keV/1.5–12 keV (BAT/ASM). To reduce large uncertainties the light curves were rebinned and then the HR were computed. Like all hardness ratios, these are instrumentally dependent. We can see that there is a smooth hardening evolution of the source before the reversal, although from this figure we cannot observe any dramatic change a posteriori.

In the bottom panel of Fig 4 we have replaced the intensity with the BAT count rate in order to perform Hardness–intensity diagram (HID). This allow us to study the long-term spectral variability of 4U 1626–67, including the transition, since the 2 *RXTE* observations do not provide us any direct comparison between before and after the torque reversal. From that figure we can see that there is a transition from hard to soft during this new reversal of 4U 1626–67.

6. DISCUSSION

The discovery of the torque reversal in 2008 (see Fig 5) has shown the spin behavior of 4U 1626–67 to be more complicated than previously thought. While the continuous decrease of total X-ray flux during almost two decades was expected to bring the source into quiescence (Krauss et al. 2007), a new spin reversal with a rapid increase of the flux occurred. This inconsistency reopens discussion on physical processes governing the spin evolution of the pulsar, and raises a question about the nature of the new torque reversal.

All previous studies of 4U 1626–67 were focused

on modeling the spin-up torque applied to the neutron star from the accreted material. It was widely believed that the spin behavior of the pulsar depended mainly on variations of the mass accretion rate onto the stellar surface and therefore, the rate of mass transfer between the system components. An attempt to explain the torque reversal in 1990 (the spin-up to spin-down transition) in terms of variable equilibrium period (Ghosh and Lamb 1979) has been made by Vaughan and Kitamoto (1997). The neutron star phase transition in their model is associated with a substantial decrease of mass accretion rate and, possibly, change of the

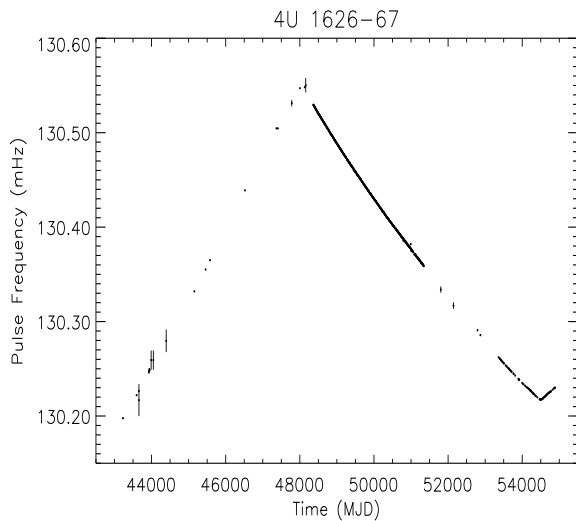


Fig. 5.— Pulse frequency history of 4U 1626–67 from 1997 up to 2009. The 1990 June and the 2008 Feb reversals are clearly seen.

structure of the accretion flow beyond the magnetosphere. This scenario is based on some evidence for a connection between torque and X-ray luminosity in 4U 1626–67 and a hardening of the energy spectrum after the torque reversal. They have emphasized, however, that this approach encounters major difficulties explaining the observed behavior of QPOs, which have been interpreted in terms of the magnetospheric beat-frequency oscillations (Lamb et al. 1985). Their analysis suggests that either this interpretation of QPOs is incorrect or the torque reversal in 1990 occurred as the magnetospheric radius of the neutron star, r_m , had increased beyond its corotation radius, which for the

parameters of 4U 1626–67 is (Lamb et al. 1973)

$$r_c = \left(\frac{GM_{\text{ns}}}{4\pi^2\nu^2} \right)^{1/3} \simeq 6.7 \times 10^8 m^{1/3} P_{7.7}^{2/3} \text{ cm.} \quad (1)$$

Here m and $P_{7.7}$ are the mass and spin period of the neutron star in units of $1.4 M_\odot$ and 7.7 s . A dramatic change in the power spectra between the last observation of 4U 1626–67 during the spin-down phase (2003) (Kaur et al. 2008), and observations made soon after the new torque reversal has been recently reported by Jain et al. (2009), with the 35–48 mHz QPO no longer being present, and wide shoulders on the pulse fundamental appearing. They claimed that the observed behavior of the source cannot be a simple case of increased mass transfer rate, but is also a change in the accretion flow parameters.

Analyzing the evolution of the source energy spectrum and possible correlation between the torque and X-ray luminosity of the pulsar, Yi and Vishniac (1999) proposed a scenario in which the torque reversal in 1990 is associated with a state transition of the accretion disk to a geometrically thick, hot and, possibly, sub-Keplerian phase. Following this idea one could associate the 2008 torque reversal with an inverse transition of the disk into its previous geometrically thin Keplerian phase. However, the reason for such a transition is rather unclear since the level of X-ray flux measured before and even after the 2008 reversal is smaller than that measured during the reversal in 1990. Furthermore, both reversals have occurred at almost the same timescale (about 150 days), which significantly exceeds the dynamical timescale in the hot disk in which its transition to the ground state is expected. A difficulty to fit in the transition timescales observed in 4U 1626–67 has also been mentioned by Wijers and Pringle (1999), who discussed a possibility to explain the torque reversals in terms of the warped disk transition into a retrograde regime.

A correlation between the torque applied to the neutron star in 4U 1626–67 and X-ray flux of the system in the above mentioned models has been adopted as one of the basic assumptions. To test the validity of this assumption using data derived before 1993 was rather complicated. This is illustrated in Figure 6, which shows the 4U 1626–67 X-ray flux history. We can see all previous

flux measurements and two *RXTE*/PCA recent values from the present work (in the 2–20 keV band). These values are relative to the flux measured in 1978 by *HEAO 1* in the same energy band (Orlandini et al. 1998; Krauss et al. 2007; Chakrabarty et al. 1997, and references therein). The cross point before the 2008 reversal has been inferred by scaling the PCA fluxes according to the observed change (2.5 factor) in the *Swift*/BAT rate, since no spectral changes across the transition have been observed according to the present work. It should be noted, however, that all these relative flux values were computed in different energy bands, therefore the general decreasing trend we see since 1977 might not be the real picture. Points could misrepresent the *HEAO 1* 0.7–60 keV flux by a $\sim 20\%$ due to spectral changes. Moreover, rather than a continuous decline (ignoring the 1990 point) 4U 1626–67 might present a flat behavior until the first reversal, then a sudden drop after that and a decreasing tendency until the 2008 reversal, in which this source experienced a rapid increase of flux. It therefore appears that the spin-down phase is the only suitable part of the light curve for testing the correlation between the torque and mass accretion rate onto the neutron star surface.

As seen from Figure 6, the X-ray flux during the spin-down phase has decreased by a factor of 2. This indicates that the mass accretion rate onto the surface of the neutron star, \dot{M} , and, correspondingly, the spin-up torque applied to the star (Pringle and Rees 1972),

$$K_{\text{su}} = \dot{M}(GM_{\text{ns}}r_{\text{m}})^{1/2}, \quad (2)$$

during this phase have also decreased by at least the same value. If the spin-down torque applied to the neutron star during this time were constant one would expect the pulsar to brake harder at its fainter state close to the end of the spin-down phase. However, observations show the situation to be just the opposite. The spin-down rate of the neutron star during this phase has decreased from $|\dot{\nu}| \simeq 7 \times 10^{-13} \text{ Hz s}^{-1}$ (Chakrabarty et al. 1997) to $5 \times 10^{-13} \text{ Hz s}^{-1}$ (see Figure ??), implying that the pulsar was braking harder at its brighter stage just after the torque reversal in 1990. According to the equation governing spin evolution of an accreting neutron star,

$$2\pi I \dot{\nu} = K_{\text{su}} - K_{\text{sd}}, \quad (3)$$

this means that the spin-down torque, K_{sd} , during the spin-down phase has been decreasing simultaneously with the spin-up torque but at a higher rate and, therefore, the pulsar spin evolution during this time has been governed mainly by variations of K_{sd} rather than K_{su} (here I is the moment of inertia of the neutron star). This conclusion seriously challenges the possibility of modeling the spin history of 4U 1626–67 solely in terms of variations of \dot{M} , and suggests that the dramatic increase of X-ray flux observed in 2008 torque reversal may be a consequence rather than a reason for this event.

With the lack of correlation between the X-ray flux and the torque applied to the neutron star, modeling of the spin-down torque appears to be the main target for theoretical studies of the system. Unfortunately, this part of modeling of the magneto-rotational evolution of neutron stars remains so far a work in progress. The canonical prescription for the spin-down torque (Lipunov 1992),

$$K_{\text{sd}} = k_{\text{t}} \frac{\mu^2}{r_{\text{c}}^3}, \quad (4)$$

in our case turns out to be rather ineffective. The dipole magnetic moment of the neutron star, μ , during the spin-down phase obviously remains constant and the corotation radius, changes only by 0.16% ($\Delta r_{\text{c}} \lesssim 1.1 \times 10^6 \text{ cm}$) as it follows from the observed changes of the pulsar frequency ($|\Delta \nu| \simeq 3.3 \times 10^{-4}$). Hence, any variation of K_{sd} under these conditions proves to be determined by the dimensionless parameter $k_{\text{t}} < 1$, which in the case of disk accretion is just the α parameter at the inner radius of the disk (Lipunov 1992, and references therein). However, it appears to be rather difficult to combine the assumption about significant variation of turbulence at the inner radius of the disk with the extremely low level of noise strength observed in 4U 1626–67 (Chakrabarty et al. 1997). Furthermore, different rates of variations of K_{sd} and K_{su} during the spin-down phase indicates that either k_{t} is a non-linear function of α , or the expression (4) is oversimplified, and in the case of 4U 1626–67 is ineffective. As recently shown by Perna et al. (2006), the spin-down torque proves to be a strongly dependent on the relative velocity between the disk and magnetosphere and its value significantly varies even for a relatively small variations of the mass-transfer

rate if the interaction between that disk and the magnetosphere occurs at the corotation radius of the star. They proposed a model where simultaneous with accretion from a disk onto the neutron star some material from near the disk – magnetosphere boundary is ejected and either escapes from the system or is recycled back into the accretion disk. This results in a hysteresis-type limit cycle where slow changes in the accretion rate from the companion into the accretion disk can result in the rapid change in torque and luminosity. Their model predicts, however, that the luminosity after a spin-down to spin-up torque reversal would be higher than the luminosity after a spin-up to spin-down torque reversal, which is the opposite of what occurred for 4U 1626-67 for this new reversal. Moreover, for 4U 1626-67 they predicted the full spin-down/spin-up cycle would take thousands of years, again inconsistent with the present observations. It should be noted, however, that the cycle could be interrupted by a sudden increase of the mass transfer rate in the disk. The brightening of the pulsar observed during the torque reversal in 2008 does not allow us to exclude this possibility.

The above mentioned problems may indicate that the torque applied to the star should be treated in a different way (see, e.g. Rappaport et al. 2004), or the interaction between the disk and magnetosphere in 4U 1626-67 occurs in a particular region, in which small perturbations of pulsar parameters may lead to dramatic changes in the torque and mass accretion rate. As shown by Anzer and Boerner (1980, 1983), the boundary between the disk and magnetosphere is subject to Kelvin-Helmholtz instability in a region specified with the condition

$$|r_c - r_m| \lesssim \delta_c, \quad (5)$$

while apart of this region the interchange-type instabilities of the boundary are suppressed. Here δ_c is the thickness of region where the velocity difference between the disk and magnetosphere is smaller than the sound velocity of plasma in the disk, i.e. $|V_k(r_m \pm \delta_c) - V_k(r_c)| \lesssim V_s$. Here $V_k(r) = (GM_{ns}/r)^{1/2}$ is the Keplerian velocity, and V_s is the sound speed at the inner radius of the disk. The value of δ_c is model dependent, but eventually is of the order of the disk thickness (Anzer and Boerner 1983; Lovelace et al. 1995). For the conditions of interest $\delta_c \sim 3 \times 10^6$ cm,

which is comparable with the amplitude of variation of the corotation radius during the spin-down phase 1990-2008 inferred from our observations. This represents some grounds to assume that the spin and intensity evolution of 4U 1626-67 can be governed by variation of relative position of r_c and r_m in the region specified by condition (5). Since $\Delta r_c \simeq (1/2)\delta_c$ one could expect that the spin-up/spin-down cycle of the pulsar is determined mainly by variations of its corotation radius, while the magnetospheric radius remains almost constant. The recurrent time of the cycle in this case would be $\sim 15 - 25$ year, which is close to the observed value. Further analysis of the corresponding scenario is, however, beyond the scope of this paper. Here we would like to note only that 4U 1626-67 represents an exceptional case as an accretion-powered pulsar with an extremely small torque noise. This indicates that the accretion picture in this system may differ significantly from that realized in other pulsars.

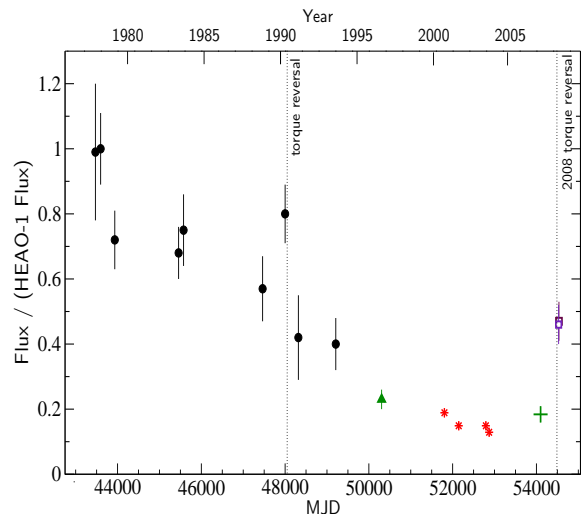


Fig. 6.— The X-ray flux history of 4U 1626-67 relative to the flux measured by *HEAO 1*, in the same energy band, from previous works (Chakrabarty et al. (1997): circles; Orlandini et al. (1998): triangle; Krauss et al. (2007): stars) and two recent *RXTE*/PCA observations (unfilled squares) in the 2–20 keV band. The cross point is inferred from PCA flux and the fractional change in the *Swift*/BAT rate, since no spectral changes during the transition have been observed in this work.

Finally, the spectral evolution of 4U 1626-67 during the torque reversal differs from that expected in models which suggest significant changes of the accretion flow structure in spin-up/spin-down transitions (e.g. Yi and Vishniac 1999; Wijers and Pringle 1999). As seen from Figure 4, the spectrum becomes the hardest during the reversal and the value of the hardness ratio before and after these events does not differ significantly. This indicates that the recent torque reversal can be associated with changes of physical conditions in the inner part of the disk or/and in the region of its interaction with the magnetosphere rather than a significant change of the accretion flow geometry. The errors of the observations are, however, too large for a justification of particular transition model. A more precise spectral measurements of the pulsar during its next spin-up/spin-down transition is, therefore, strongly desired. Assuming the recurrent time of the transition to be about 18 years one can suggest to pay more attention to the pulsar in 2025–2028. Since the typical duration of the transition is about 150 days, a regular monitoring of the pulsar, frequently enough to provide a spin-up rate measurement every two months, would prevent us from missing its next torque reversal.

7. CONCLUSIONS

We report on a discovery of a new spin-down to spin-up torque reversal in 4U 1626-67. It occurred after about 18 years of the pulsar’s steadily spinning down and was centered on 2008 Feb 4. The transition lasted ~ 150 days and accompanied by an increase in the *Swift*/BAT count rate of a 2.5 factor ($\sim 150\%$). The pulsar spectrum was harder during the torque transition than before or after. A strong correlation between torque and luminosity is inferred only during the transition. The spin-up and spin-down rates before and after the transition were almost identical ($\sim |\dot{\nu}| = 5 \times 10^{-13} \text{ Hz s}^{-1}$). However, the pulsar was braking harder at the beginning of the spin-down epoch in 1990 than at its end in 2008. Furthermore, the spin-down rate during this epoch was decreasing simultaneously with the decreasing of the source X-ray luminosity. Finally, the spin-down to spin-up torque reversal in 2008 has occurred at lower luminosity as the spin-up to spin-down torque in 1990. These properties cannot be explained with

existing models and appear to be a clue for further progress in understanding the mechanism governing the torque reversals in the accretion-powered pulsars.

Acknowledgments. A.C.A. thanks for the support of this project to the Spanish Ministerio de Ciencia e Innovación through the 2008 postdoctoral program MICINN/Fulbright under grant 2008-0116. N.R.I. acknowledges supported from NASA Postdoctoral Program at NASA Marshall Space Flight Center, administered by Oak Ridge Associated Universities through a contract with NASA, and support from Russian Foundation of Basic Research under the grant 07-02-00535a. M.H.F. acknowledges support from NASA grant NNX08AG12G. We also want to thank all the *Fermi*/GBM team for its help.

REFERENCES

- Anzer, U. and Boerner, G.: 1980, *A&A* **83**, 133
- Anzer, U. and Boerner, G.: 1983, *A&A* **122**, 73
- Bildsten, L., Chakrabarty, D., Chiu, J., Finger, M. H., Grunsfeld, J. M., Koh, T., Prince, T. A., and Wilson, R.: 1994, in C. E. Fichtel, N. Gehrels, and J. P. Norris (eds.), *American Institute of Physics Conference Series*, Vol. 304 of *American Institute of Physics Conference Series*, pp 294–298
- Bildsten, L., Chakrabarty, D., Chiu, J., Finger, M. H., Koh, D. T., Nelson, R. W., Prince, T. A., Rubin, B. C., Scott, D. M., Stollberg, M., Vaughan, B. A., Wilson, C. A., and Wilson, R. B.: 1997, *ApJS* **113**, 367
- Bradt, H. V., Rothschild, R. E., and Swank, J. H.: 1993, *A&AS* **97**, 355
- Chakrabarty, D.: 1998, *ApJ* **492**, 342
- Chakrabarty, D., Bildsten, L., Grunsfeld, J. M., Koh, D. T., Prince, T. A., Vaughan, B. A., Finger, M. H., Scott, D. M., and Wilson, R. B.: 1997, *ApJ* **474**, 414
- Chakrabarty, D., Wang, Z., Juett, A. M., Lee, J. C., and Roche, P.: 2002, *ApJ* **573**, 789
- Day, C. S. R. and Stevens, I. R.: 1993, *ApJ* **403**, 322

- Deeter, J. E., Boynton, P. E., Lamb, F. K., and Zylstra, G.: 1989, *ApJ* **336**, 376
- Dupree, A. K., Gursky, H., Black, J. H., Davis, R. J., Hartmann, L., Matilsky, T., Raymond, J. C., Hammerschlag-Hensberge, G., van den Heuvel, E. P. J., Burger, M., Lamers, H. J. G. L. M., Vanden Bout, P. A., Morton, D. C., de Loore, C., van Dessel, E. L., Menzies, J. W., Whitelock, P. A., Watson, M., Sanford, P. W., and Pollard, G. S. G.: 1980, *ApJ* **238**, 969
- Finger, M. H., Bildsten, L., Chakrabarty, D., Prince, T. A., Scott, D. M., Wilson, C. A., Wilson, R. B., and Zhang, S. N.: 1999, *ApJ* **517**, 449
- Fritz, S., Kreykenbohm, I., Wilms, J., Staubert, R., Bayazit, F., Pottschmidt, K., Rodriguez, J., and Santangelo, A.: 2006, *A&A* **458**, 885
- Gehrels, N., Chincarini, G., Giommi, P., Mason, K. O., and et al.: 2004, *ApJ* **611**, 1005
- Ghosh, P. and Lamb, F. K.: 1979, *ApJ* **234**, 296
- Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., and Tananbaum, H.: 1972, *ApJ* **178**, 281
- Gruber, D. E., Blanco, P. R., Heindl, W. A., Pelling, M. R., Rothschild, R. E., and Hink, P. L.: 1996, *A&AS* **120**, C641+
- Hinkle, K. H., Fekel, F. C., Joyce, R. R., Wood, P. R., Smith, V. V., and Lebzelter, T.: 2006, *ApJ* **641**, 479
- Inam, S. Ç., Şahiner, Ş., and Baykal, A.: 2009, *MNRAS* **395**, 1015
- Jahoda, K., Swank, J. H., Giles, A. B., Stark, M. J., Strohmayer, T., Zhang, W., and Morgan, E. H.: 1996, in O. H. Siegmund and M. A. Gummin (eds.), *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 2808 of *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, pp 59–70
- Jain, C., Paul, B., and Dutta, A.: 2009, *ArXiv e-prints*
- Kaur, R., Paul, B., Kumar, B., and Sagar, R.: 2008, *ApJ* **676**, 1184
- Kommers, J. M., Chakrabarty, D., and Lewin, W. H. G.: 1998, *ApJ* **497**, L33+
- Krauss, M. I., Schulz, N. S., Chakrabarty, D., Juett, A. M., and Cottam, J.: 2007, *ApJ* **660**, 605
- Krivoson, R., Produit, N., Kreykenbohm, I., Staubert, R., von Kienlin, A., Winkler, C., and Gehrels, N.: 2003, *The Astronomer's Telegram* **211**, 1
- Lamb, F. K., Pethick, C. J., and Pines, D.: 1973, *ApJ* **184**, 271
- Lamb, F. K., Shibasaki, N., Alpar, M. A., and Shaham, J.: 1985, *Nature* **317**, 681
- Levine, A., Ma, C. P., McClintock, J., Rappaport, S., van der Klis, M., and Verbunt, F.: 1988, *ApJ* **327**, 732
- Levine, A. M., Bradt, H., Cui, W., Jernigan, J. G., Morgan, E. H., Remillard, R., Shirey, R. E., and Smith, D. A.: 1996, *ApJ* **469**, L33+
- Lipunov, V. M.: 1992, *Astrophysics of Neutron Stars. Springer-Verlag Berlin, Heidelberg. Editor: Lipunov, V. M. and Börner, G. and Wadhwa, R. S.*
- Lovelace, R. V. E., Romanova, M. M., and Bisnovaty-Kogan, G. S.: 1995, *MNRAS* **275**, 244
- McClintock, J. E., Bradt, H. V., Doxsey, R. E., Jernigan, J. G., Canizares, C. R., and Hiltner, W. A.: 1977, *Nature* **270**, 320
- McClintock, J. E., Li, F. K., Canizares, C. R., and Grindlay, J. E.: 1980, *ApJ* **235**, L81
- Meegan, C. A. e. a.: 2009, *ApJ*
- Middleditch, J., Mason, K. O., Nelson, J. E., and White, N. E.: 1981, *ApJ* **244**, 1001
- Orlandini, M., Fiume, D. D., Frontera, F., del Sordo, S., Piraino, S., Santangelo, A., Segreto, A., Oosterbroek, T., and Parmar, A. N.: 1998, *ApJ* **500**, L163+

- Paczynski, B. and Sienkiewicz, R.: 1981, *ApJ* **248**, L27
- Perna, R., Bozzo, E., and Stella, L.: 2006, *ApJ* **639**, 363
- Pettersson, J. A., Rothschild, R. E., and Gruber, D. E.: 1991, *ApJ* **378**, 696
- Pravdo, S. H., White, N. E., Boldt, E. A., Holt, S. S., Serlemitsos, P. J., Swank, J. H., Szymkowiak, A. E., Tuohy, I., and Garmire, G.: 1979, *ApJ* **231**, 912
- Pringle, J. E. and Rees, M. J.: 1972, *A&A* **21**, 1
- Rappaport, S., Markert, T., Li, F. K., Clark, G. W., Jernigan, J. G., and McClintock, J. E.: 1977, *ApJ* **217**, L29
- Rappaport, S. A., Fregeau, J. M., and Spruit, H.: 2004, *ApJ* **606**, 436
- Reynolds, A. P., Quaintrell, H., Still, M. D., Roche, P., Chakrabarty, D., and Levine, S. E.: 1997, *MNRAS* **288**, 43
- Shinoda, K., Kii, T., Mitsuda, K., Nagase, F., Tanaka, Y., Makishima, K., and Shibasaki, N.: 1990, *PASJ* **42**, L27
- Vaughan, B. A. and Kitamoto, S.: 1997, *ArXiv Astrophysics e-prints*
- Wijers, R. A. M. J. and Pringle, J. E.: 1999, *MNRAS* **308**, 207
- Wilson, R. B., Fishman, G. J., Finger, M. H., Pendleton, G. N., Prince, T. A., and Chakrabarty, D.: 1993, in M. Friedlander, N. Gehrels, and D. J. Macomb (eds.), *American Institute of Physics Conference Series*, Vol. 280 of *American Institute of Physics Conference Series*, pp 291–302
- Yi, I. and Vishniac, E. T.: 1999, *ApJ* **516**, L87